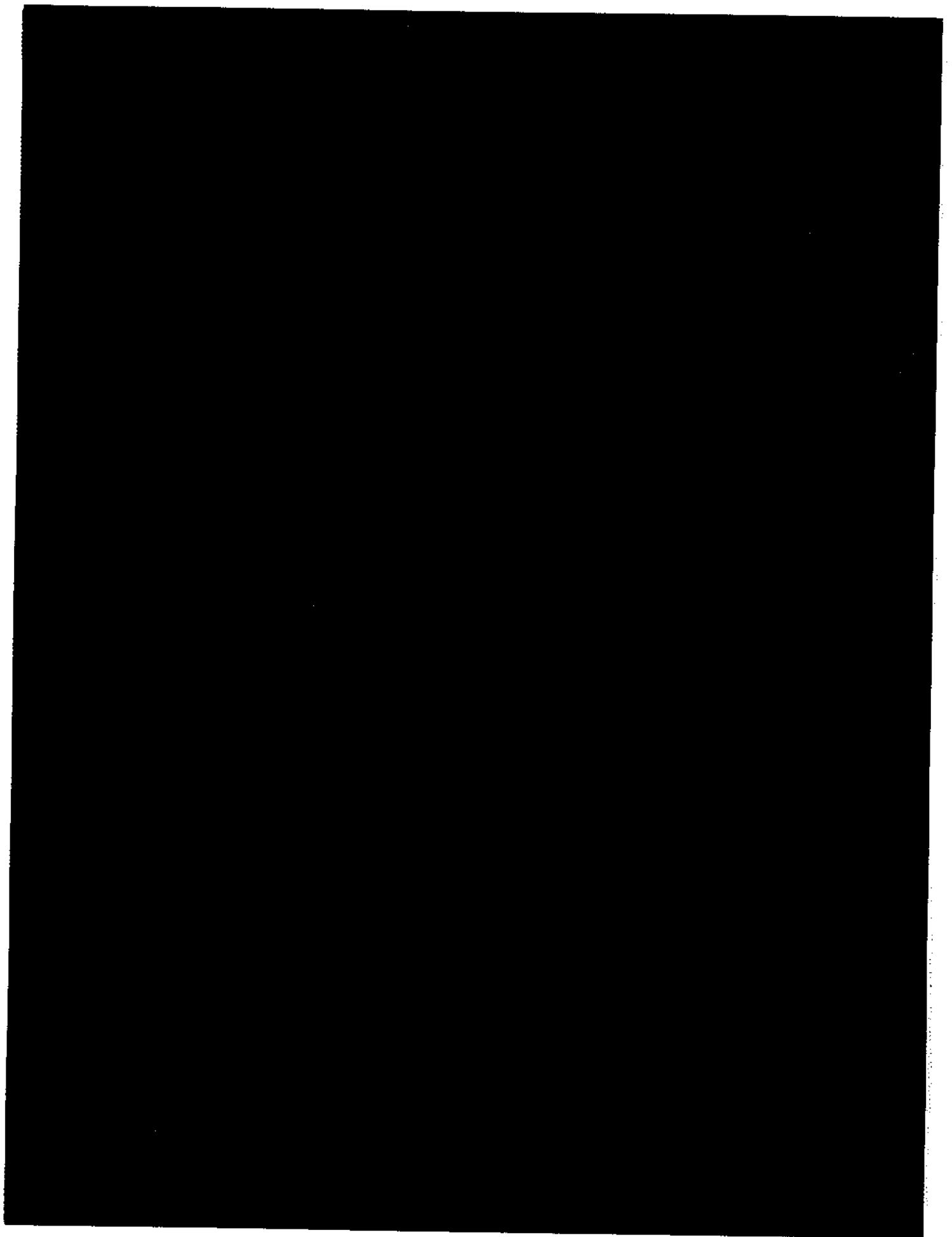


# **WHAT WE NOW KNOW ABOUT QUINTESSENCE**

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- I. OF WHAT IS THE UNIVERSE MADE?**
- II. THE DARK ENERGY DENSITY IS NOW EXACTLY OR NEARLY STATIC**
- III. ATTRACTOR PHASEPORTRAITS: SAME TRACKERS IN B-ERA, DIFFERENT CURVATURE: NOW**
- IV. INVERSE POWER POTENTIALS: LARGE CURVATURE REQUIRE FINE-TUNED INITIAL CONDITIONS**
- V. CONCLUSIONS: ACCEPTABLE QUINTESSENCE TRACKS EARLY, BUT CRAWLS NOW**





Quintessence!

fire, air,  
water, soil!

# UNIVERSE EVOLUTION

$$\begin{aligned} &= -\log(H_0) \\ N &= \ln a \\ a_0 &= 1 \end{aligned}$$

- $\rho_{cr0} = 3M_P^2 H_0^2$

$$\Omega_L = \frac{\rho_L}{\rho} = \text{FRACTION AT SCALE}$$

- Clustered Matter:  $\Omega_{B0} = 0.045$      $\Omega_{DM} = 0.225$

- Homogeneous Dark Matter ("Smooth Energy") WMAP, LSS, Supernovae, Cosmic Shear  $\rightarrow$  Cosmological Parameters:

$$\bar{w}_{Q0} \approx -0.78 \text{ (95\% CL)}$$

$$\approx \left(\frac{\rho}{\rho}\right)_Q$$

- $\Omega_{Q0} = 0.71 \pm 0.07$ ,  $w_{Q0} < -0.78$  (95% CL),  $\equiv H_0/100 = 0.72 \pm 0.05$

- Smooth Energy Now Dominates the Universe,  $\rightarrow$  Cosmological Acceleration

$$\Omega_b = 0.045$$

from nucleosynthesis,  
cosmic background radiation

□  $\Omega_m = 0.27$

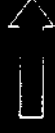
□ total “matter”

□

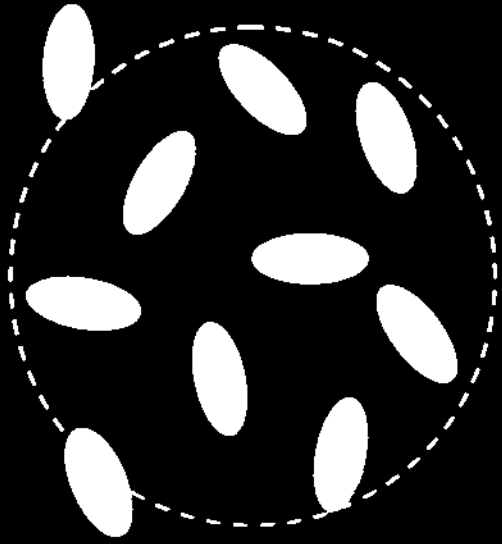
□

□ Every local mass concentration  $\Rightarrow$   
gravitational potential

□

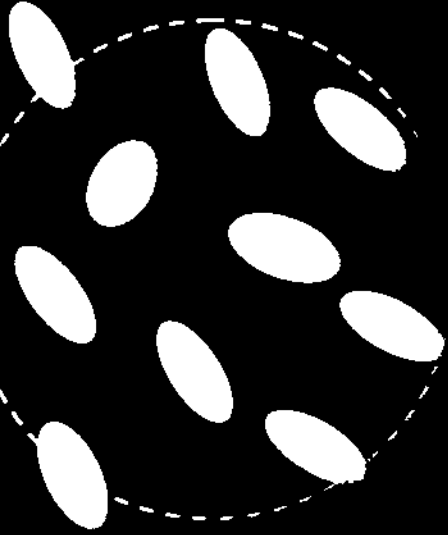


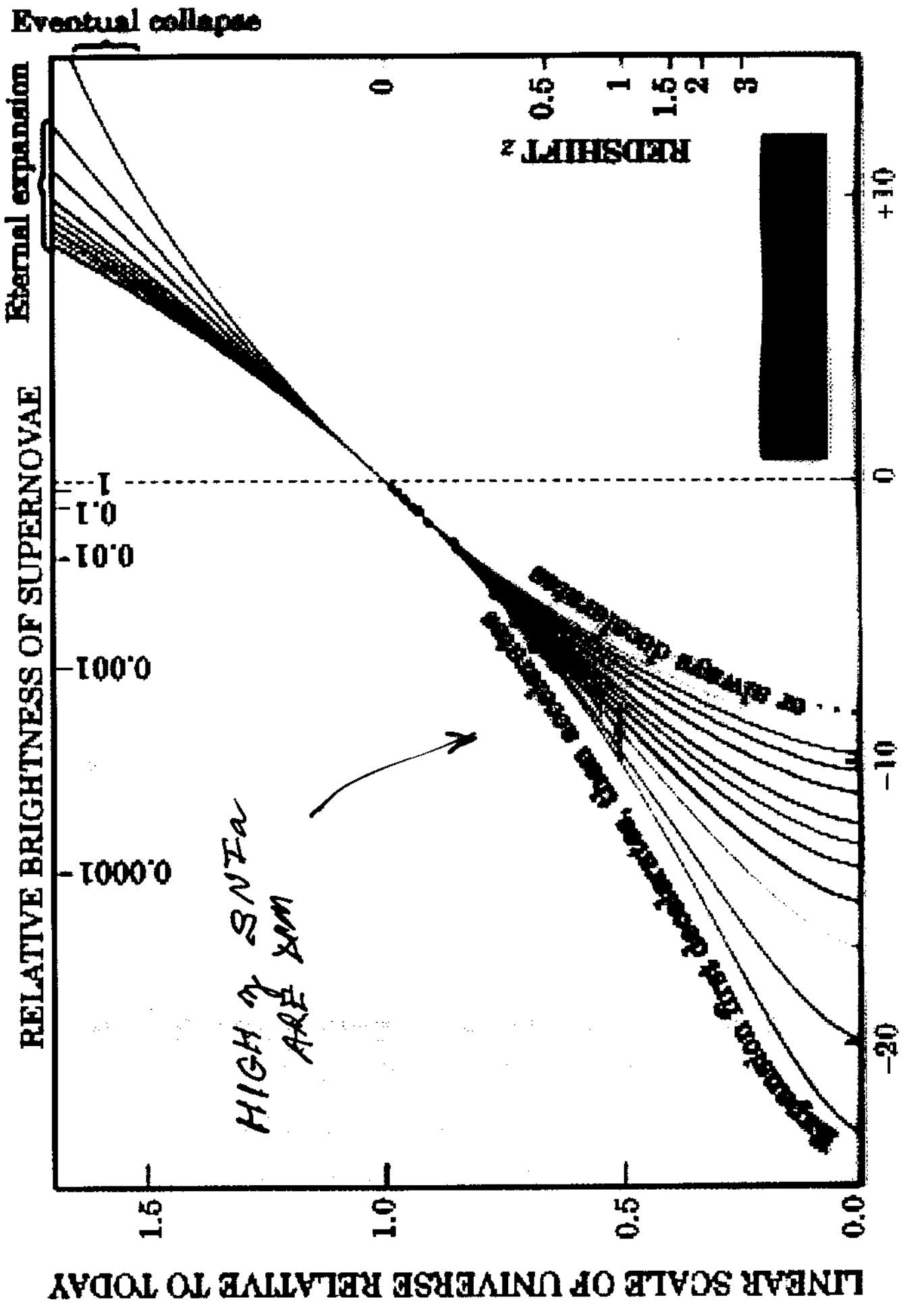
**Shear estimate**



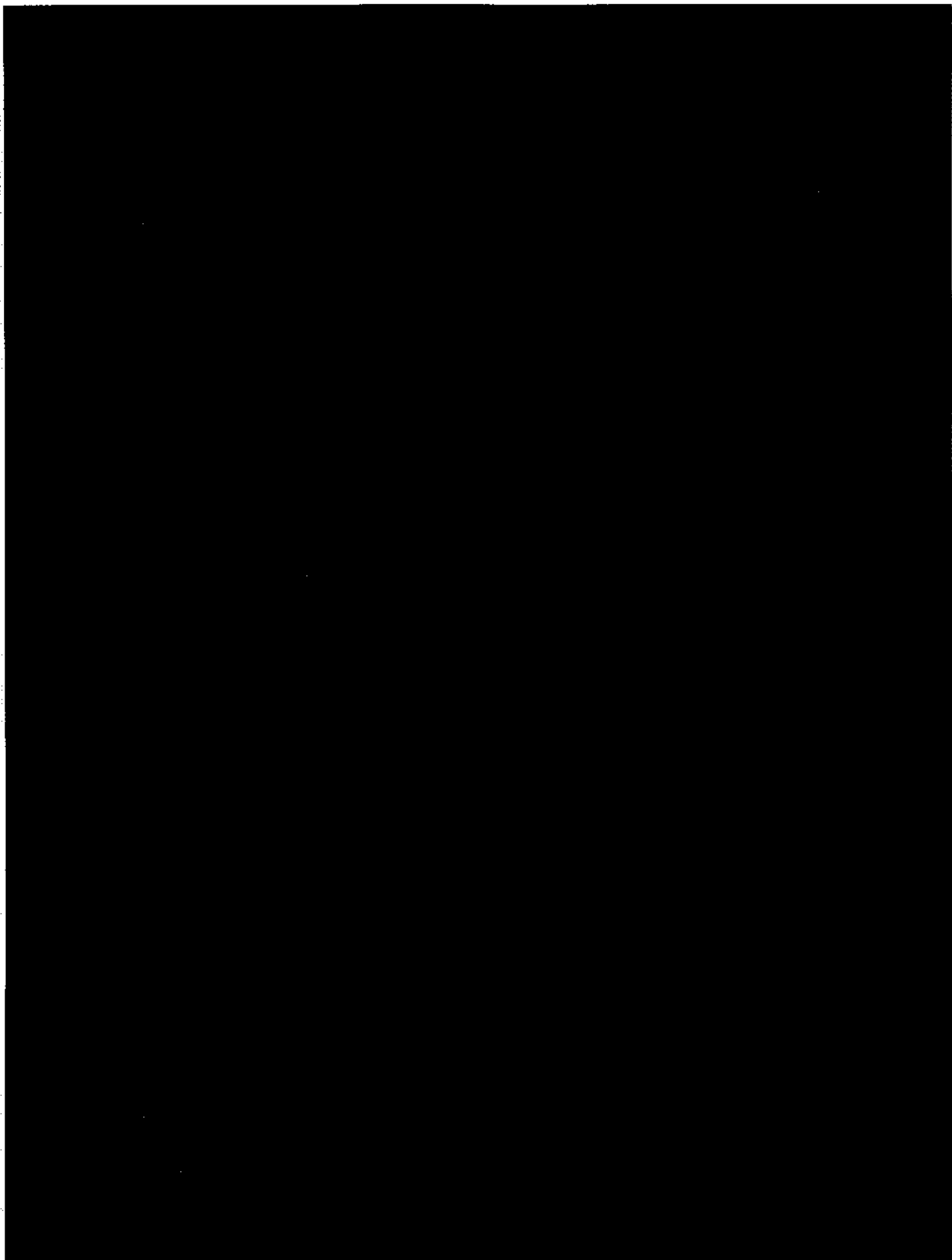
(randomly

aligned)









1

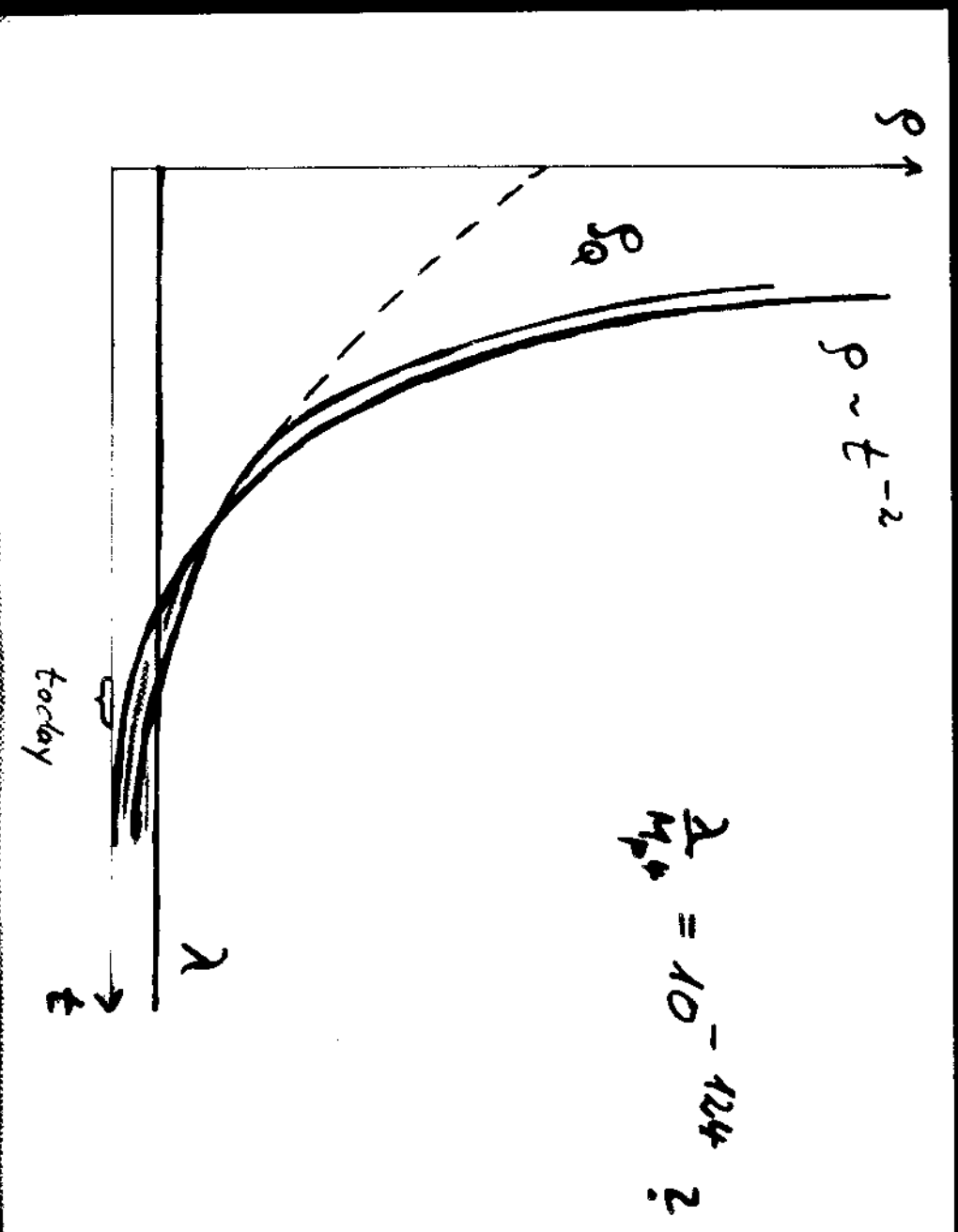
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# Cosm. Const. | Quintessence

static | dynamical



## II. THE DARK ENERGY DENSITY IS NOW EXACTLY OR NEARLY STATIC

- Dynamical Smooth Energy=Scalar Field  $\phi$  Rolling Down Its Potential=Quintessence. Explains
  - Present Small Value of Smooth Energy Density  $\approx 10^{-120} M_P^4$
  - If quintessence potential vanishes asymptotically (no cosmological constant), then no future (de Sitter) horizon: Maintains causal connection, asymptotic states, S-matrix

## Scalar Field Equation of Motion

$$\ddot{\phi} + 3H\dot{\phi} + dV/d\phi = 0,$$

$$\rho_Q = \dot{\phi}^2/2 + V(\phi), \quad P/c^2 = \dot{\phi}^2/2 - V(\phi)$$

- Alternate phase variables  $x^2 \equiv \dot{\phi}^2/2\rho, y^2 \equiv V_Q/\rho$

$$x^2 + y^2 = \Omega_Q \quad y/x = \sqrt{\frac{P/c^2}{\rho}}$$

$$dx/dN = -3x + \lambda\sqrt{3/2}y^2 + 3xy/2$$

$$dy/dN = -\lambda\sqrt{3/2}xy + 3y\gamma/2$$

$$d\lambda/dN = -\sqrt{6}\lambda^2(\Gamma - 1)$$

$$\text{SCALE FACTOR } \mathcal{N} = \log a = -\log(M_0/g)$$

- roll  $\lambda \equiv -M_P d \ln V / d\phi$  fast in background-dominated era

### III. ATTRACTORS IN BOTH TRACKING & QUINTESSENCE ERAS

Quintessence dynamics has attractor properties, making present solution insensitive to more-or-less broad range of initial conditions:

- Far future:  $w_Q \rightarrow -1, \Omega_Q \rightarrow 1$ : **asymptotically de Sitter**
- Background-dominated *past*,  $\Omega_Q \ll 1$ . **Tracking** provided:

$$\beta(\phi) \approx \text{const} \gg 1$$

ROLL IS

SLOW-ROLLING  $\frac{d(\frac{1}{2})}{dN} \equiv \frac{1}{\beta}$

POTENTIAL'S CURVATURE

$$\eta \equiv \frac{d^2V}{V d(\ln\phi)^2} = \alpha^2 \left(1 + \frac{1}{\beta}\right)$$

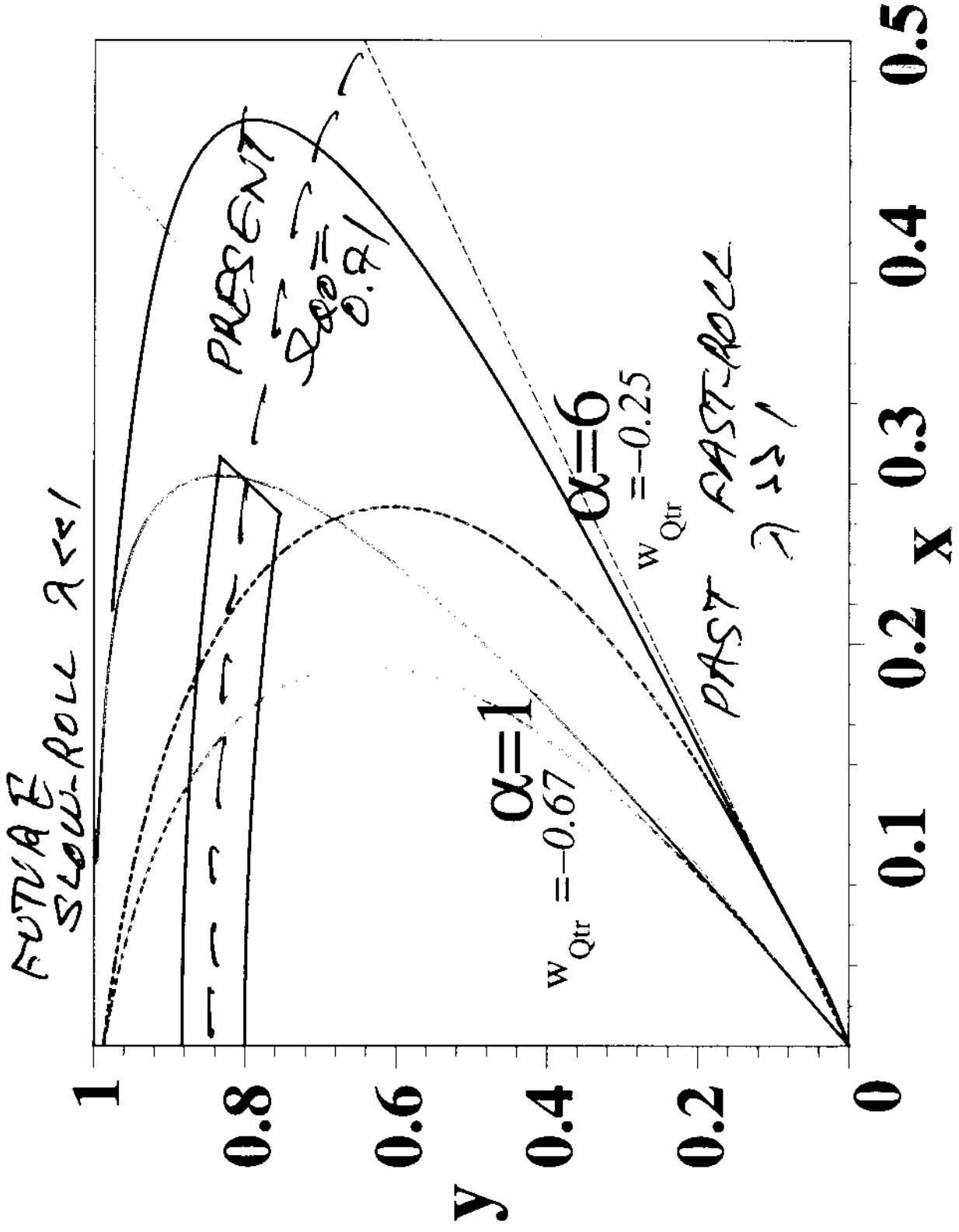
### III. ATTRACTOR PHASE PORTRAITS: SAME TRACKERS IN B-ERA, DIFFERENT CURVATURES

NOW

$$\text{INVERSE POWER } \nu = \frac{M^{4+2\alpha}}{\phi R}$$

- Steep potential  $\alpha = 6$ : tracks well, still fast-rolling now  

$$\text{PRESENT } \frac{\phi}{M^p} = \alpha \phi \sim 1$$
- Shallow potential  $\alpha = 1$ : always slow-rolling, tracks poorly, quits tracker early







## IV. INVERSE POWER POTENTIALS: LARGE CURVATURE REQUIRE FINE-TUNDED INITIAL CONDITIONS

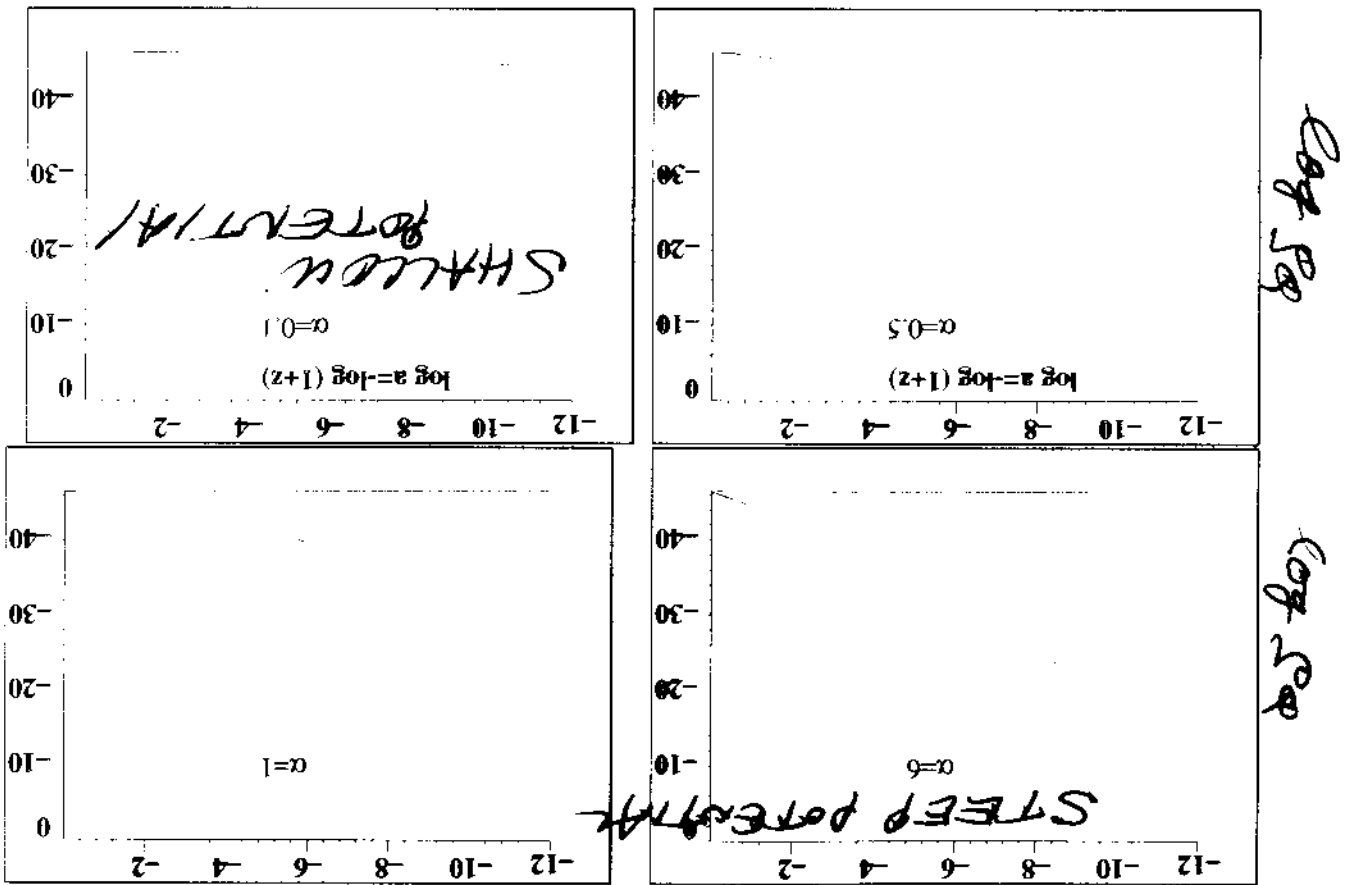
- Ideal Tracker (in B-era): curvature  $\beta = const > 1$

$$V(\phi) = M^{4+\beta} / \phi^\beta,$$

- Observed  $w_{Q0} < -0.78$  requires  $\beta < 1$
- But  $\beta < 1$  makes a **Poor Tracker**: Tracks Only from Narrow Basins of Attraction; **crawls** to present universe

Figure 1: Evolution of quintessence energy density  $\log \rho_Q(\text{GeV}^4)$  for four inverse power potentials  $\alpha = 6, 1, 0.5, 0.1$ , from red-shift  $z = 10^{12}$ , to the present value  $\rho_Q = 0.71 \rho_{cr0}$ . In all figures, the central, trajectory is the attractor, starting with tracker slope  $d \ln \rho_Q / dN = -6\gamma_B / (2 + \alpha)$ . The lower curve is the maximal undershoot trajectory, which freezes immediately and then crawls slowly to join the attractor now. The upper curve is the maximal overshoot trajectory, which kinates with slope -6, before freezing late and now reaching the attractor.

Venice 12.5.03



# THE DARK ENERGY DENSITY IS NOW EXACTLY OR NEARLY STATIC

Table 1: Tracker and present ( $\Omega_{Q0} = 0.71$ ) attractor solutions for inverse power potentials.

| $\alpha$ | $w_{Qtr}$      | $M$      | $w_{Q0}$ | $\eta_0$ | $\text{Re} \lambda_0$ | $\pi\phi_0$ | <i>BASSAN RIFTON</i><br>$\log \Omega_{Q_i}$ range |
|----------|----------------|----------|----------|----------|-----------------------|-------------|---|
| 6        | 0..-0.25       | 5.3 PeV  | -0.41    | 2.69     | 1.519(fast)           | 3.949       | -42..-0.5   |
| 1        | -0.555..-0.667 | 2.3 keV  | -0.76    | 1.65     | 0.908                 | 1.101       | -41..-1.5   |
| 0.5      | -0.733..-0.80  | 4.8 eV   | -0.86    | 1.42     | 0.689                 | 0.73        | -42.1..-9.1                                       |
| 0.1      | -0.937..-0.952 | 12.1 meV | -0.97    | 1.36     | 0.351(slow)           | 0.285       | -42.2..-35.5                                      |
| 0        | -1             | 2.5 meV  | -1       | 0        | 0 (static)            | -           | -44.1   |

## V. CONCLUSIONS: ACCEPTABLE QUINTESSENCE TRACKS EARLY, BUT CRAWLS NOW

$$\omega_{\text{eff}} \approx 1/5 \text{ ?}$$

For observed  $\tilde{w}_{Q_0} < -0.78$  (95% C.L.):

- Inverse power potentials require  $\beta = \text{const} < 1$ : poor tracker, **crawls** to present
- Admissible potentials now require  $\beta(\phi)$  increasing: large potential curvature, recent quintessence-dominance and cosmological acceleration  
e.g. **quantum** models:
  - \* Supergravity-inspired models  $V \propto \phi^{-|\alpha|} \cdot \exp(\kappa\phi)^2/2$
  - \* Albrecht and Skordis  $V \propto \phi^u \times \exp(\lambda\phi)^\beta$

- Requires fine-tuning of potential and/or initial conditions, that tracking hoped to avoid
- Now **two** cosmic coincidences: smooth energy must now be small **and** equation of state  $w_Q(z) = (P/\rho)_Q$ , fast-changing in narrow interval  $-1 < w_Q < -0.78$ . We live at a very special time (anthropic reasoning)!
- Quintessence hardly distinguishable from cosmological constant it was invoked to avoid: hard to reconstruct Q potential or to distinguish from cosmological constant.